AEDC-TSR-81-V13



# WIND TUNNEL TESTS OF THE SPACE SHUTTLE FOAM INSULATION WITH SIMULATED DEBONDED REGIONS

D. W. Stallings and A. S. Hartman

Calspan Field Services, Inc.

April 1981

Final Report for Period 5 March 1981

Approved for public release; distribution unlimited.



**ARNOLD ENGINEERING DEVELOPMENT CENTER**
**ARNOLD AIR FORCE STATION, TENNESSEE**
**AIR FORCE SYSTEMS COMMAND**
**UNITED STATES AIR FORCE**

## NOTICES

When U. S. Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.

## APPROVAL STATEMENT

This report has been reviewed and approved.

J. T. Best

J. T. BEST
Aeronautical System Division
Deputy for Operations

Approved for publication:

FOR THE COMMANDER

J M Rampy

JOHN M. RAMPY
Assistant Deputy for Aerospace
Flight Dynamics Testing
Deputy for Operations

UNCLASSIFIED

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>AEDC-TSR-81-V13 | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>Wind Tunnel Tests of the Space Shuttle Foam Insulation with Simulated Debonded Regions | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final Report<br>March 5, 1981 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>D. W. Stallings and A. S. Hartman,<br>Calspan Field Services, Inc. | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Arnold Engineering Development Center<br>Air Force Systems Command<br>Arnold Air Force Station, TN 37389 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>Program Element 921E02<br>Control Number 9E02 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>NASA/MSFC<br>Marshall Space Flight Center<br>Huntsville, AL 35812 | | 12. REPORT DATE<br>April 1981 |
| | | 13. NUMBER OF PAGES<br>33 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report)<br>Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE<br>N/A |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in Defense Technical Information Center (DTIC)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Space Shuttle
external tank
aerodynamic heating
materials testing
heat transfer
foam insulation


20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Wind tunnel tests of the Space Shuttle foam insulation with simulated debonded regions were conducted in the von Karman Gas Dynamics Facility Tunnel C. The tests were conducted to investigate the survivability of the external tank protection system with a hole in the insulation caused by area debonding and insulation tear-out. The material samples were tested using the wedge technique. The tests were run at a free-stream Mach No. 10 and a free-stream total temperature of 1900°R. The wedge angle was varied to provide test conditions which were representative of those expected during launch. Selected results are presented to illustrate the test techniques and typical data obtained.


DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

CONTENTS



APPENDIXES

## NOMENCLATURE

| | |
|---|---|
| ALPHI | Indicated pitch angle, deg |
| B | Width of wedge, 15 in. (see Fig. 5b) |
| CR | Center of rotation, axial station along the tunnel centerline about which the model rotates in pitch, in. |
| d | Distance measured from downstream edge of cutout; positive downstream (see Figs. 3b and c) |
| E | Gardon gage output, mv |
| GAGE | Gardon gage number |
| H(FP) | Heat-transfer coefficient derived from previous calibration tests $H(FP) = 2.198 \times 10^{-4} \times WA + 3.67 \times 10^{-4}$, $Btu/ft^2\text{-sec-}^\circ R$ (see Appendix III) |
| H(TT) | Heat-transfer coefficient based on TT, QDOT/(TT-TW), $Btu/ft^2\text{-sec-}^\circ R$ |
| ITT | Enthalpy based on TT, Btu/lbm |
| KG | Gardon gage temperature calibration factor, °R/mv |
| L | Total length of wedge, 41.5 in. (see Fig. 5b) |
| M | Free-stream Mach number |
| MU | Dynamic viscosity based on free-stream temperature, $lbf\text{-sec}/ft^2$ |
| P | Free-stream static pressure, psia |
| PIC NO. | Picture number |
| PT | Tunnel stilling chamber pressure, psia |
| Q | Free-stream dynamic pressure, psia |
| QDOT | Heat-transfer rate, $Btu/ft^2\text{-sec}$ |
| QDOT-0 | Calculated heat-transfer rate based on 0°F wall temperature, (i.e., TW = 460°R), $Btu/ft^2\text{-sec}$ |

| | |
|---|---|
| RE | Free-stream unit Reynolds number, $ft^{-1}$ |
| RHO | Free-stream density, $lbm/ft^3$ |
| RUN | Data set identification number |
| S1 | Gage sensitivity |
| S2 | Calculated gage sensitivity<br>S2 = S1 * f(TGE) |
| SAMPLE | Material specimen identification designation |
| T | Free-stream static temperature, °R |
| TGE | Gardon gage edge temperature, °R |
| TGDEL | Temperature differential from the center to the edge of Gardon gage disc, °R |
| TIME | Elapsed time from lift-off, sec |
| TIMECL | Time at which the model reached tunnel centerline, Central Standard Time |
| TIMEEXP | Time of exposure to the tunnel flow when the data were recorded<br>[TIME - $(\frac{32}{57})$(TIME INJ)]; sec |
| TIMEEXPT | Total exposure time for a RUN, sec |
| TIMEINJ | Elapsed time from lift-off to arrival at tunnel centerline, sec |
| TT | Tunnel stilling chamber temperature, °R |
| TW | Gage wall temperature, °R |
| V | Free-stream velocity, ft/sec |
| WA | Wedge angle, deg (see Fig. 6b) |
| X,Y | Orthogonal body axis system directions (see Figs. 3b and c) |

# 1.0 INTRODUCTION

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 921E02, Control Number 9E02 at the request of the National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC), Huntsville, Alabama for the Martin Marietta Corporation (Michoud Operations), New Orleans, Louisiana. The Martin Marietta Corporation project engineer was Mr. T. L. Click, and the NASA/MSFC project managers were Mr. John Warmbrod and Mr. F. D. Bachtel. The results were obtained by Calspan Field Services Inc./AEDC Division, operating contractor for the aerospace flight dynamics testing effort at the AEDC, AFSC, Arnold Air Force Station, Tennessee. The tests were conducted in the von Karman Gas Dynamics Facility (VKF), under AEDC Project No. C342VC.

The objective of this test was to investigate the survivability of the External Tank Thermal Protection System (ET-TPS) in areas where debonding and insulation tear-out has occurred. The response of the Lightning Protection System to the test environment was also evaluated.

The tests were conducted in the 50-in.-diam Hypersonic Wind Tunnel (C) at the VKF on March 5, 1981. Data were recorded at Mach number 10 with tunnel stilling chamber conditions of 1750 psia and 1440°F. The nominal wedge angle (WA) varied from 5.0 to 23.5 deg to produce local cold-wall heating rates ranging from ~2 to 10 Btu/ft$^2$ sec.

All test data including detailed logs and other information required to use the data, have been transmitted to Martin Marietta.

Inquiries to obtain copies of the test data should be directed to NASA/MSFC/ED33, Marshall Space Flight Center, Huntsville, Alabama 35812. A microfilm record has been retained in the VKF at AEDC.

# 2.0 APPARATUS

## 2.1 TEST FACILITY

Tunnel C (Fig. 1) is a closed-circuit, hypersonic wind tunnel with a Mach number 10 axisymmetric contoured nozzle and a 50-in.-diam test section. The tunnel can be operated continuously over a range of pressure levels from 200 to 2000 psia with air supplied by the VKF main compressor plant. Stagnation temperatures sufficient to avoid air liquefaction in the test section (up to 2260°R) are obtained through the use of a natural-gas-fired combustion heater in series with an electric resistance heater. The entire tunnel (throat, nozzle, test section, and diffuser) is cooled by integral, external water jackets. The tunnel is equipped with a model injection system, which allows removal of the model from the test section while the tunnel remains in operation. A description of the tunnel may be found in Ref. 1.

## 2.2 TEST ARTICLE

A photograph of a typical test specimen is shown in Fig. 2. The specimens were basically flat insulation panels consisting of a 0.13-in. aluminum support plate covered with a 0.6-in. layer of super light ablator (SLA, Mat'l SLA-561) and a 0.75-in. layer of spray-on foam insulator (SOFI, Mat'l CPR-488). To simulate different degrees of insulation damage a hole was cut through the insulation on each panel and the SLA and SOFI were removed. Circular and rectangular hole shapes were used with dimensions as shown in Fig. 3. Two of the panels were modified to include Gardon gages in the cut-out area as shown in Figs. 3b and c.

The test panels for the Lightning Protection System were fabricated in the same manner as the others but with the insulation left intact. Strips of conducting paint of different thicknesses were placed on the foam as shown in Fig. 4.

Each test specimen was identified by a code defined by Martin Marietta. This was converted to a four-digit configuration code which could then be input to the Tunnel C data system. These codes are defined in Table 1. The insulation panels were attached to the VKF materials wedge for testing as shown in Fig. 5. Installation of the wedge in Tunnel C is illustrated in Fig. 6.

## 2.3 TEST INSTRUMENTATION

The instrumentation, recording devices, and calibration methods used to measure the primary tunnel and test data parameters are listed in Table 2a along with the estimated measurement uncertainties. The range and estimated uncertainties for primary parameters that were calculated from the measured parameters are listed in Table 2b.

A variety of cameras were used to record the test results. Color motion pictures (2 cameras) and pre- and posttest color stills recorded any changes in the samples. The movie cameras were operated at frame rates of 24 fps (see Table 3). A shadowgraph still was taken for each run to aid in visualizing the shock wave patterns and flow directions about the protuberances. A black and white video tape was also made for general coverage during the test.

The Gardon gages used in the two instrumented panels were a special high-temperature type, 0.25-in. in diameter, with a 0.010-in.-thick sensing disk. Each gage had a Chromel®-Alumel® thermocouple to provide the gage edge temperature. These temperatures, together with the gage output, were used to determine the gage surface temperatures and corresponding heat-transfer rate, which was then used to calculate the local heat-transfer coefficient.

## 3.0 TEST DESCRIPTION

### 3.1 TEST CONDITIONS

A summary of the nominal test condition is given below:

| M | PT, psia | TT, °R | $\bar{P}$, psia |
|---|---|---|---|
| 10.10 | 1750 | 1900 | 0.038 |

A test summary showing the configurations tested and the variables for each is presented in Table 4.

### 3.2 TEST PROCEDURES

In the VKF continuous flow wind tunnels (A, B, C), the model is mounted on a sting support mechanism in an installation tank directly underneath the tunnel test section. The tank is separated from the tunnel by a pair of fairing doors and a safety door. When closed, the fairing doors, except for a slot for the pitch sector, cover the opening to the tank and the safety door seals the tunnel from the tank area. After the model is prepared for a data run, the personnel access door to the installation tank is closed, the tank is vented to the tunnel flow, the safety and fairing doors are opened, the model is injected into the airstream, and the fairing doors are closed. After the data are obtained, the model is retracted into the tank and the sequence is reversed with the tank being vented to atmosphere to allow access to the model in preparation for the next run. The sequence is repeated for each configuration change.

The required local flow conditions over the insulation specimen are produced by attaching the panel to a large wedge. The oblique shock wave generated by the wedge reduces the free-stream Mach number to the desired local Mach number. Since the free-stream Mach number is fixed, the local Mach number is varied by pitching the wedge. With the free-stream Mach number and the wedge angle defined, the pressure and temperature ratios across the shock wave are established. The pressure and temperature along the wedge surface can then be set as desired by adjusting the tunnel stilling chamber pressure and temperature. A complete description of this technique as used in Tunnel C is given in Ref. 2.

For this particular test the instrumented panels posed somewhat of a problem. Normally the gages would have been installed in a nonablating panel. In this instance, because of time constraints in the test preparation phase, the gages were simply added to two of the insulation specimens. As indicated in Table 4, during Run 1 the wedge, with instrumented panel 029-03, was pitched in the tunnel to obtain data at three nominal heating rates. Ablation of the SOFI was such that when the third data point was obtained the panel configuration was significantly altered. In an attempt to correct this situation the second instrumented panel (030-07) was tested in three short injections (Runs 2, 3 and 4). Although this did not eliminate the problem, a more stable cavity shape was achieved.

## 3.3 DATA REDUCTION

Measured stilling chamber pressure and temperature and the calibrated test section Mach number are used to compute the free-stream parameters. The equations for a perfect gas isentropic expansion from stilling chamber to test section are modified to account for real-gas effects.

Data measurements, obtained from the Gardon gages, are gage output (E) and gage edge temperature (TGE). The gages are direct-reading heat-flux transducers, and the gage output is converted to heating rate by means of a laboratory-calibrated gage sensitivity (S1). The sensitivity has been found to be a function of gage temperature and therefore must be corrected for gage temperature changes,

$$S2 = S1\ f(TGE) \tag{1}$$

Heat flux to the gage is then calculated for each data point by the following equation:

$$QDOT = E/S2 \tag{2}$$

The gage wall temperature used in computing the gage heat-transfer coefficient is obtained from two measurements - the output of the gage edge thermocouple (TGE) and the temperature difference (TGDEL) from the gage center to its edge. TGDEL is proportional to the gage output, E, and is calculated by

$$TGDEL = (KG)(E) \tag{3}$$

The gage wall temperature is then computed as

$$TW = TGE + 0.75\ TGDEL \tag{4}$$

where the factor 0.75 represents the average or integrated value across the gage.

The VKF standard Gardon gage data reduction procedure was used to compute model local heat-transfer coefficients. The procedure averages five consecutive samples of gage output, (E) commencing with the data loop recorded at least one second after the model arrives at tunnel centerline. The average output is then compared to each individual reading used in the average to check for "wild" points. If the individual readings differ from the calculated average by more than ±2 percent or ±15 counts, whichever is larger, an asterisk (*) is printed next to the tabulated value of QDOT. The gage edge temperature (TGE) was averaged in the same manner with ±5 deg allowable deviation from the average.

The heat-transfer coefficient for each gage was computed using the following equation:

$$H(TT) = \frac{QDOT}{(TT - TW)} \tag{5}$$

The heat-transfer coefficient calculated from Eq. (5) was normalized using a predicted value, H(FP), for a flat plate without the cutout in the insulation. This value was taken from previous calibration test data on the same wedge model. The evaluation of H(FP) is discussed in Appendix III.

QDOT-0 is the heat flux calculated when the gage wall temperature (TW) is assumed to be 460°R. It is computed using the following equation:

$$QDOT\text{-}0 = H(TT)(TT - 460)$$

## 3.4 UNCERTAINTY OF MEASUREMENTS

In general, instrumentation calibrations and data uncertainty estimates were made using methods recognized by the National Bureau of Standards (NBS). Measurement uncertainty is a combination of bias and precision errors defined as

$$U = \pm(B + t_{95}S)$$

where B is the bias limit, S is the sample standard deviation, and $t_{95}$ is the 95th percentile point for the two-tailed Student's "t" distribution (95-percent confidence interval), which for sample sizes greater than 30 is taken equal to 2.

Estimates of the measured data uncertainties for this test are given in Table 2a. The data uncertainties for the measurements are determined from in-place calibrations through the data recording system and data reduction program.

Propagation of the bias and precision errors of measured data through the calculated data was made in accordance with Ref. 3, and the results are given in Table 2b.

# 4.0 DATA PACKAGE PRESENTATION

A complete set of all photographic data and tabulated data for this test has been provided to Martin Marietta Corporation. Photographic data which showed significant testing results and a complete set of tabulated data have been provided to NASA/Marshall Space Flight Center/ED33, Huntsville, Alabama. All test specimens for this test have been returned to the Martin Marietta Corporation.

A representative posttest photograph is shown in Fig. 7. This is the same test panel shown in the pretest photograph in Fig. 2.

A typical data plot is shown in Fig. 8. The heat-transfer coefficient at the bottom of the cut-out is plotted versus the distance from the trailing edge of the cutout. Since the nature of the test was such that the specimens were altered by the flow, it was not possible to obtain data on repeat runs. However, the gage data were observed to be well behaved, which lends confidence to the conclusion that the data quality was very good.

Because of the problem, discussed in Section 3.2, of the insulation ablating around the cavity, the heat-transfer data obtained in this test cannot be considered as an exact description of the heating at the bottom of round and rectangular cavities. However, the data did provide, as intended, an indication of the heat load which might be imposed on the substrate because of cavities formed where insulation was lost.

Samples of the tabulated data from the calibration and materials specimen runs are presented in Appendix IV. A copy of all data except photographs has been retained on microfilm at AEDC.

## REFERENCES

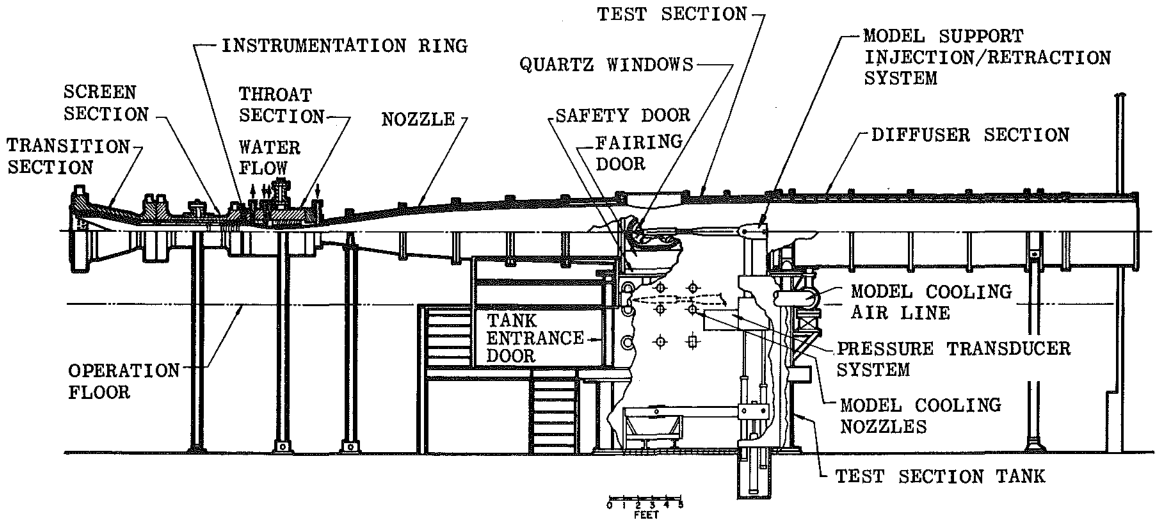

1. Test Facilities Handbook (Eleventh Edition). "von Karman Gas Dynamics Facility, Vol. 3." Arnold Engineering Development Center, June 1979.

2. Matthews, R. K. and Stallings, D. W. "Materials Testing in the VKF Continuous Flow Wind Tunnels." Presented at AIAA 9th Aerodynamic Testing Conference, Arlington, TX, June 7-9, 1976.

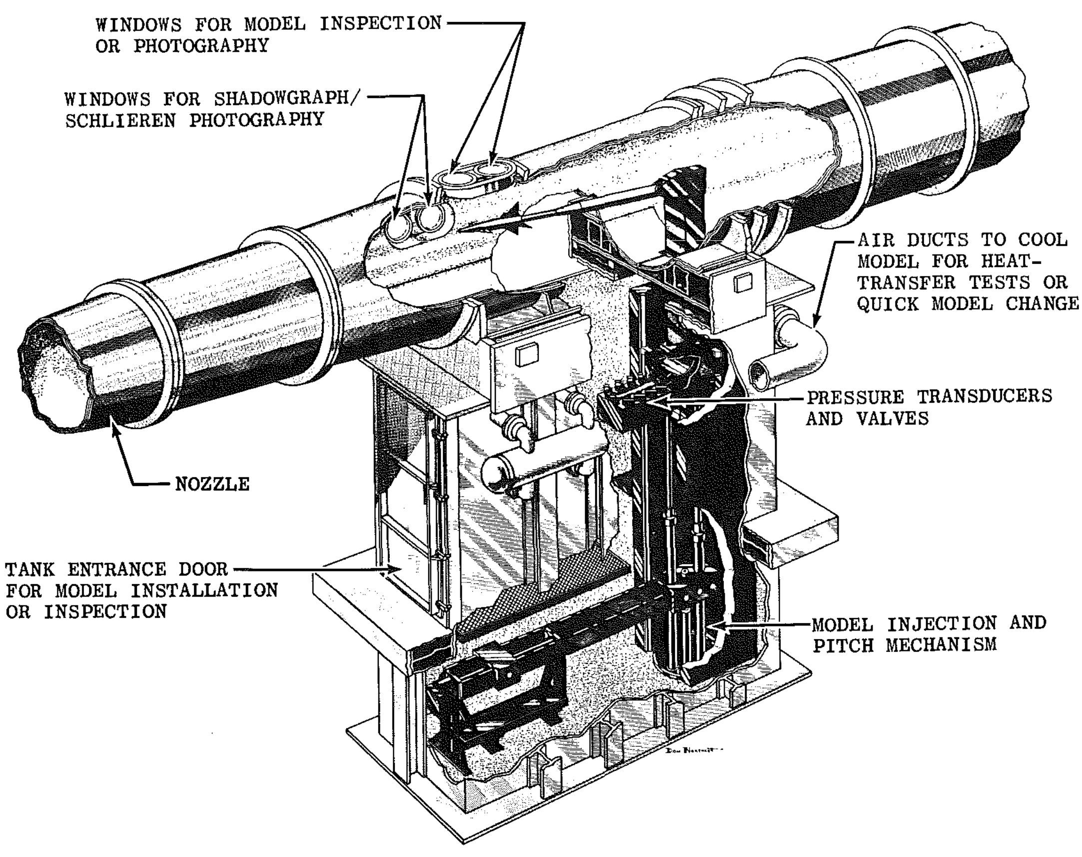
3. Abernethy, R. B. and Thompson, J. W. Jr. "Handbook - Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD755356) February 1973.

# APPENDIX I

## ILLUSTRATIONS




a. Tunnel assembly




b. Tunnel test section

Fig. 1 Tunnel C

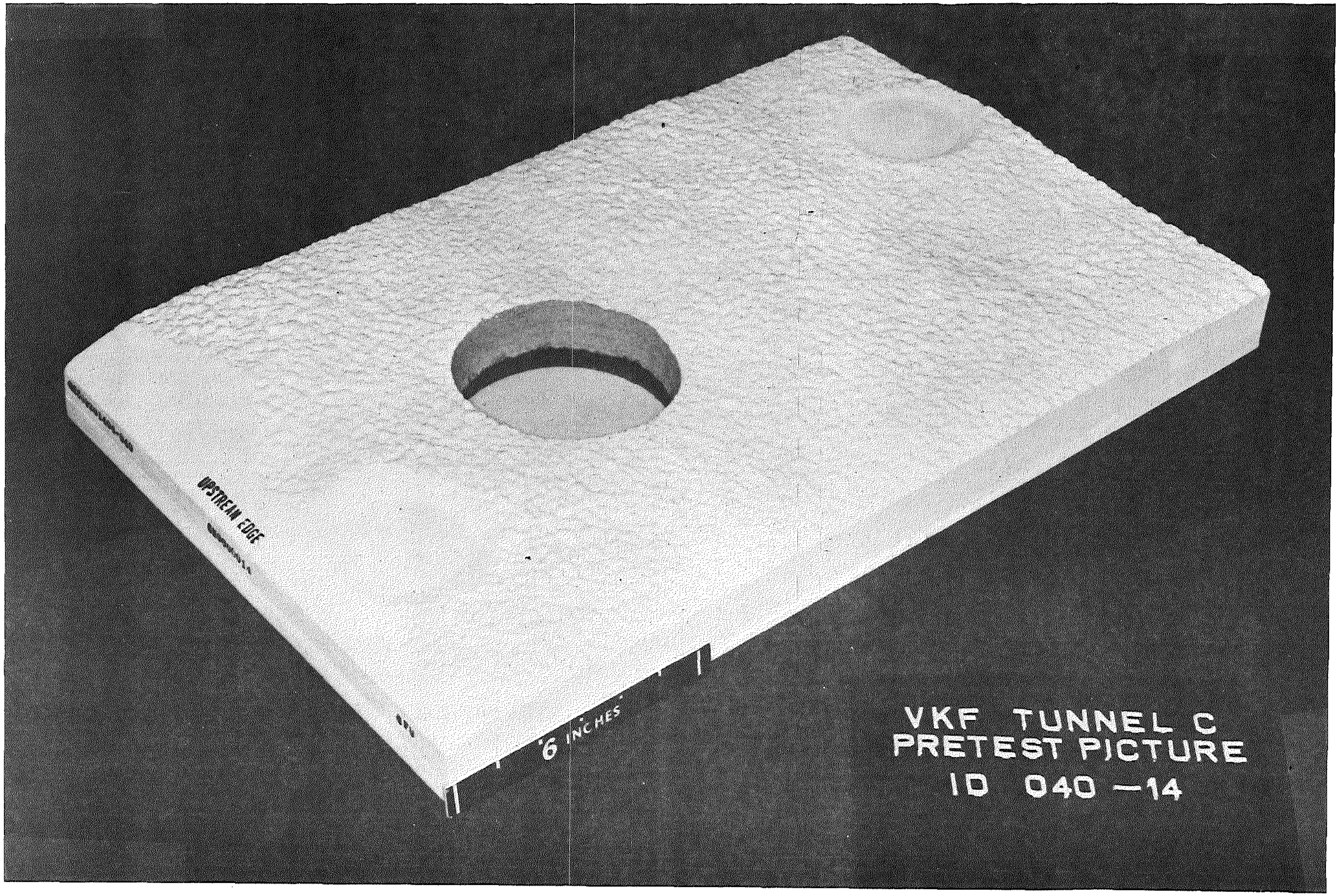
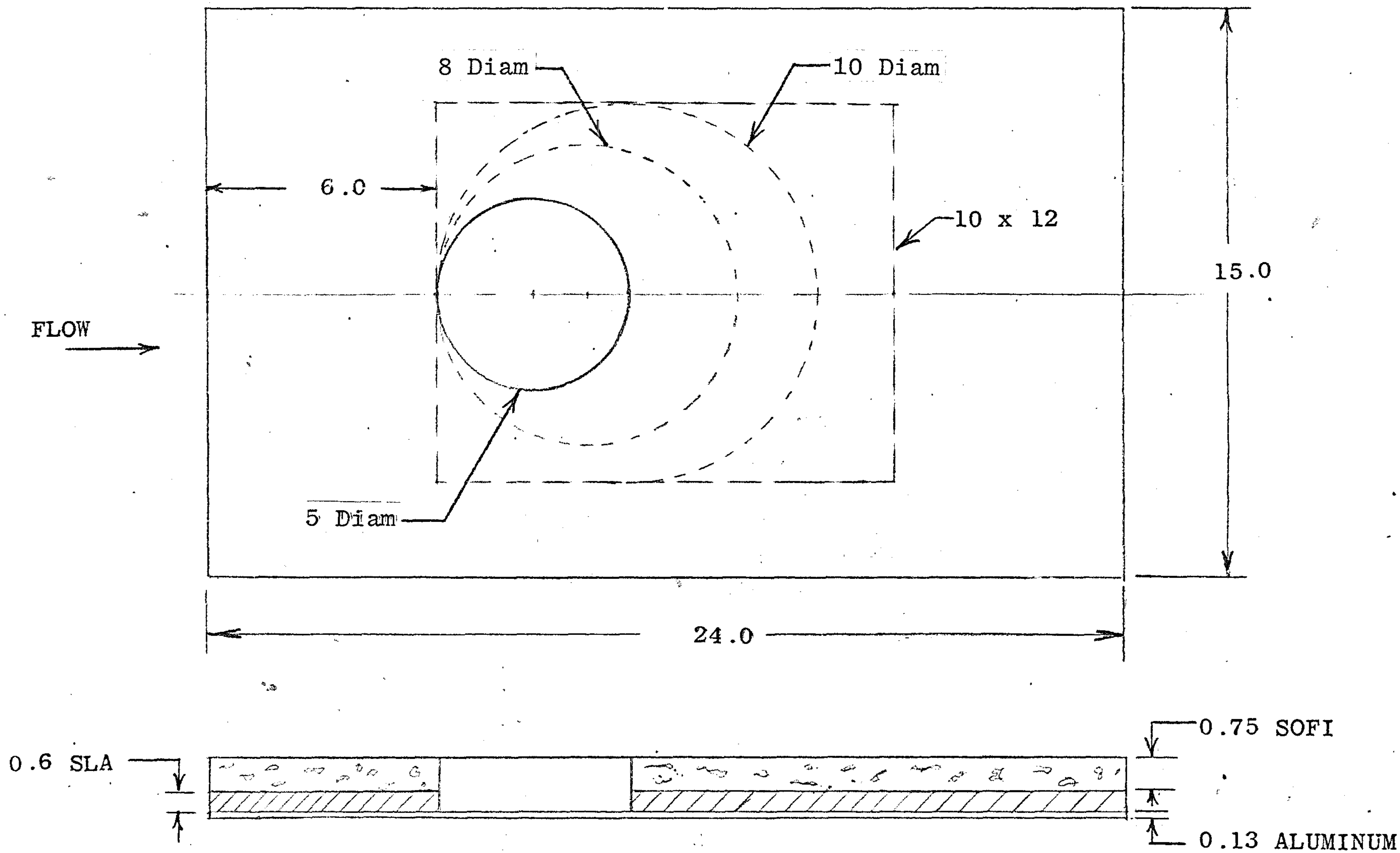


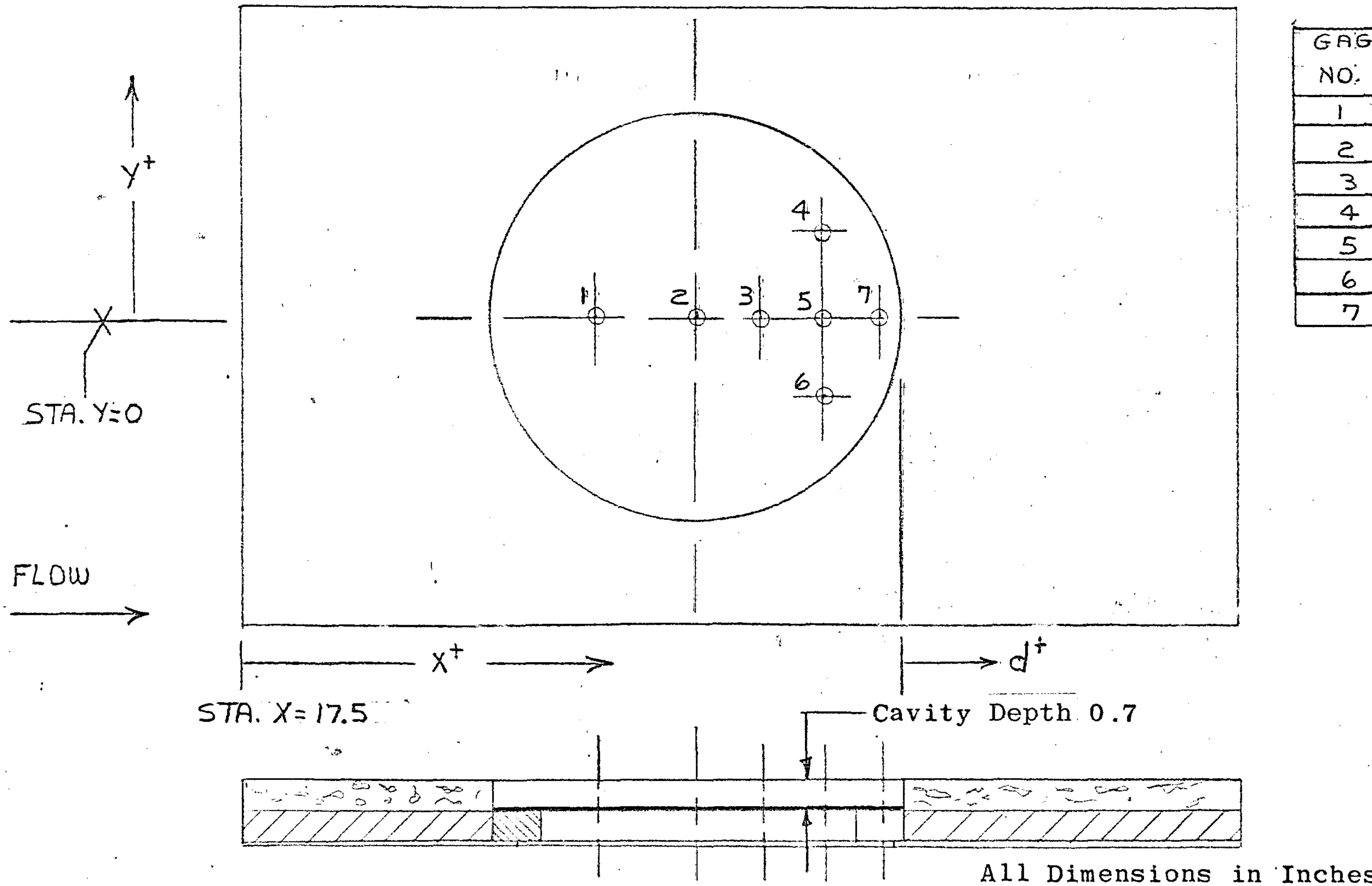

Figure 2. Typical Insulation Specimen
Pretest Photograph




All Dimensions in Inches

a. Noninstrumented Panels

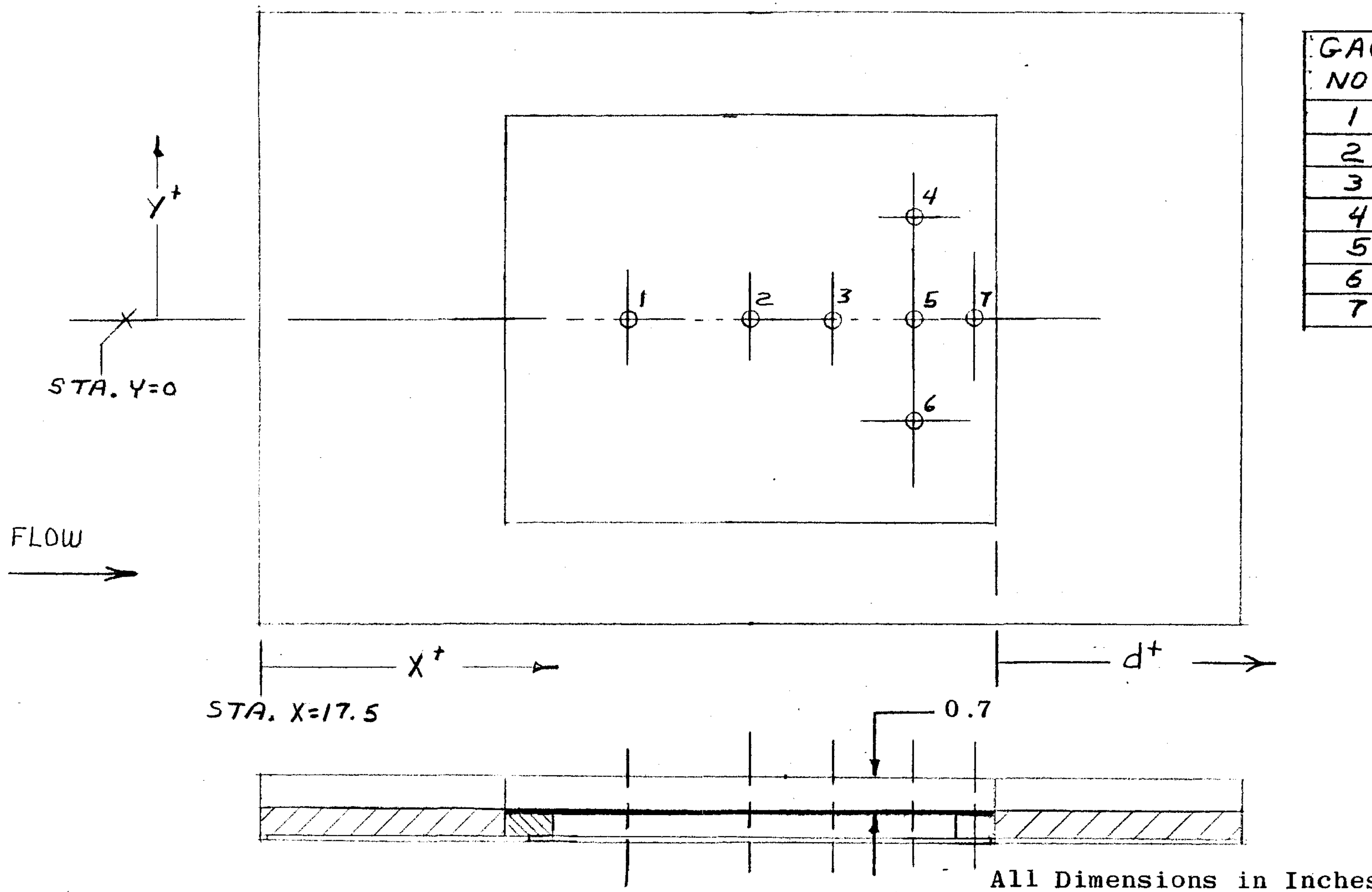
Figure 3. Sketch of Test Panel Configurations




| GAGE NO. | X | Y | d |
|---|---|---|---|
| 1 | 26.0 | 0.0 | -7.5 |
| 2 | 28.5 | 0.0 | -5.0 |
| 3 | 30.0 | 0.0 | -3.5 |
| 4 | 31.5 | 2.0 | -2.0 |
| 5 | 31.5 | 0.0 | -2.0 |
| 6 | 31.5 | -2.0 | -2.0 |
| 7 | 33.0 | 0.0 | -0.5 |

b. Instrumented Sample 030-07

Figure [illegible]. Continued




| GAGE NO. | X | Y | d |
|---|---|---|---|
| 1 | 26.5 | 0.0 | -9.0 |
| 2 | 29.5 | 0.0 | -6.0 |
| 3 | 31.5 | 0.0 | -4.0 |
| 4 | 33.5 | 2.5 | -2.0 |
| 5 | 33.5 | 0.0 | -2.0 |
| 6 | 33.5 | -2.5 | -2.0 |
| 7 | 35.0 | 0.0 | -0.5 |

c. Instrumented Sample 029-03

Figure 3. Concluded

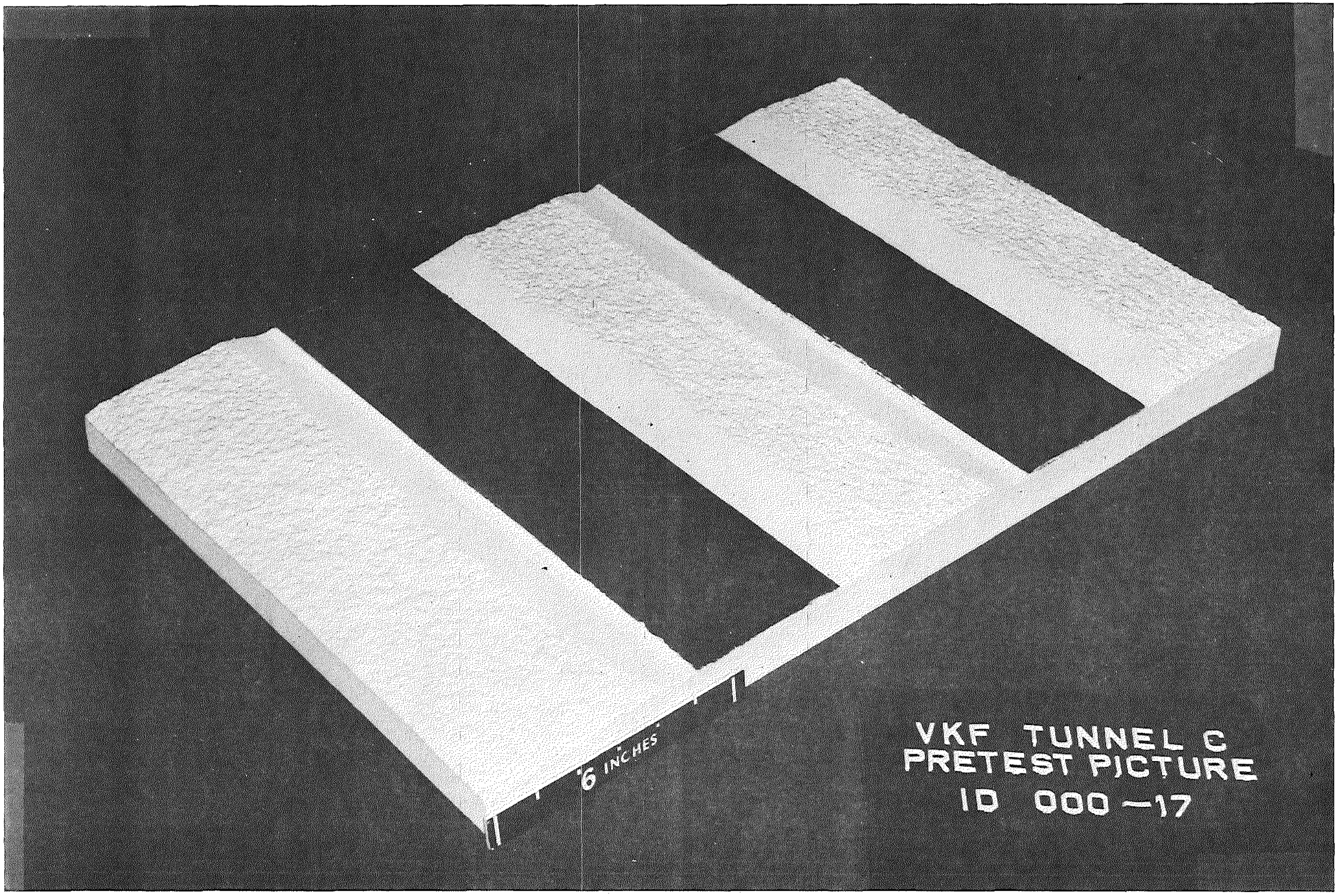
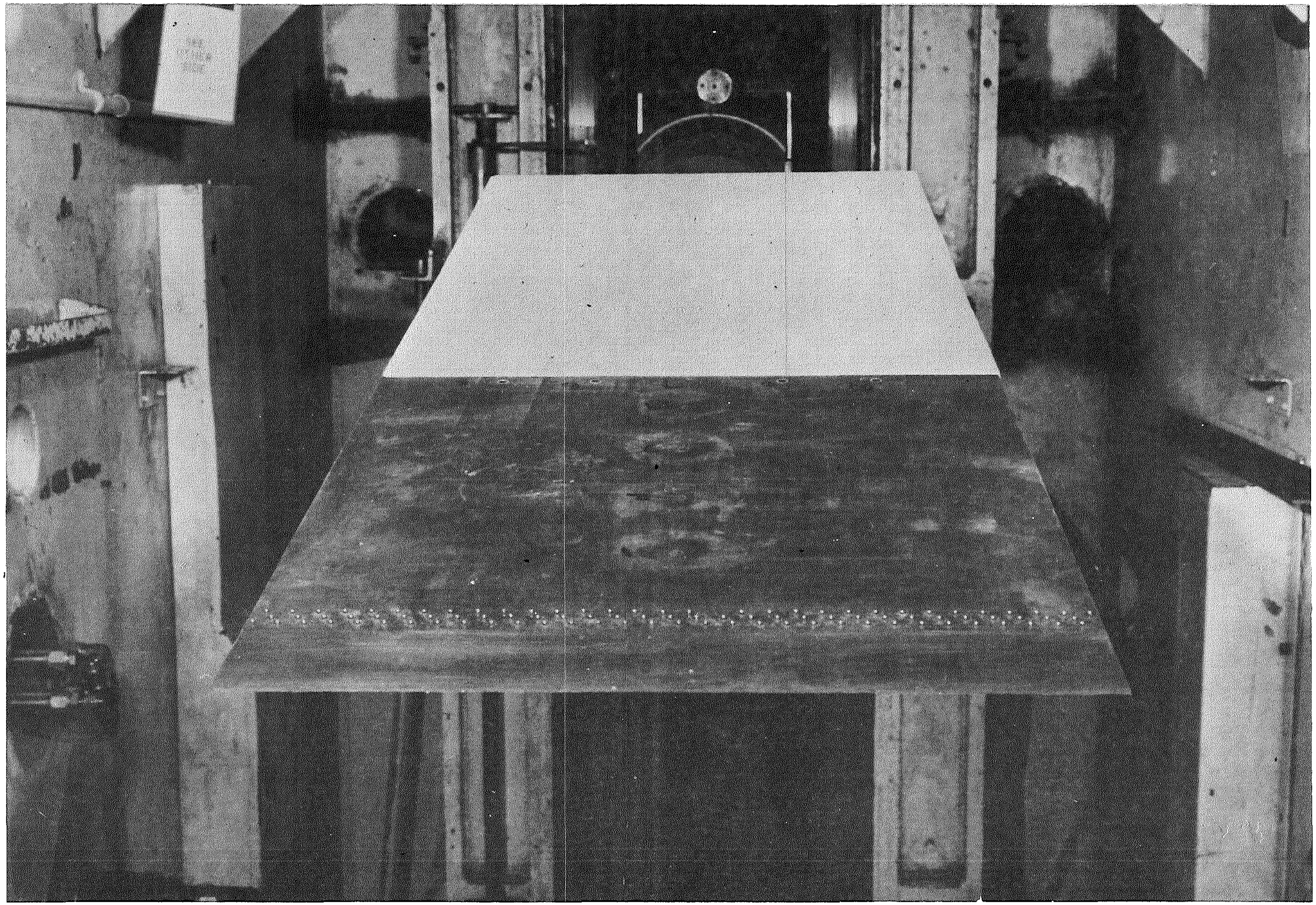
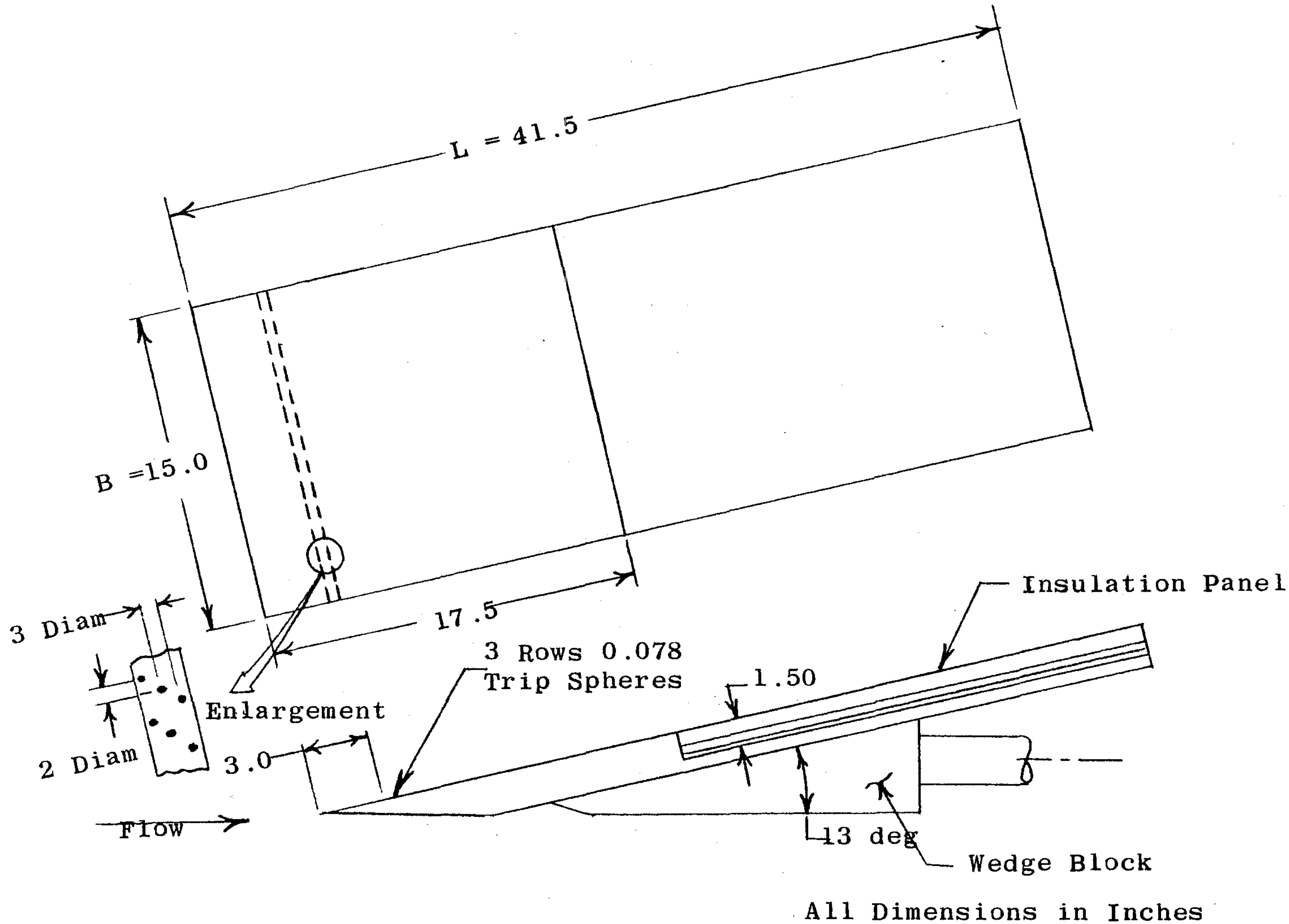



Figure 4. Specimen with Lightning Protection System



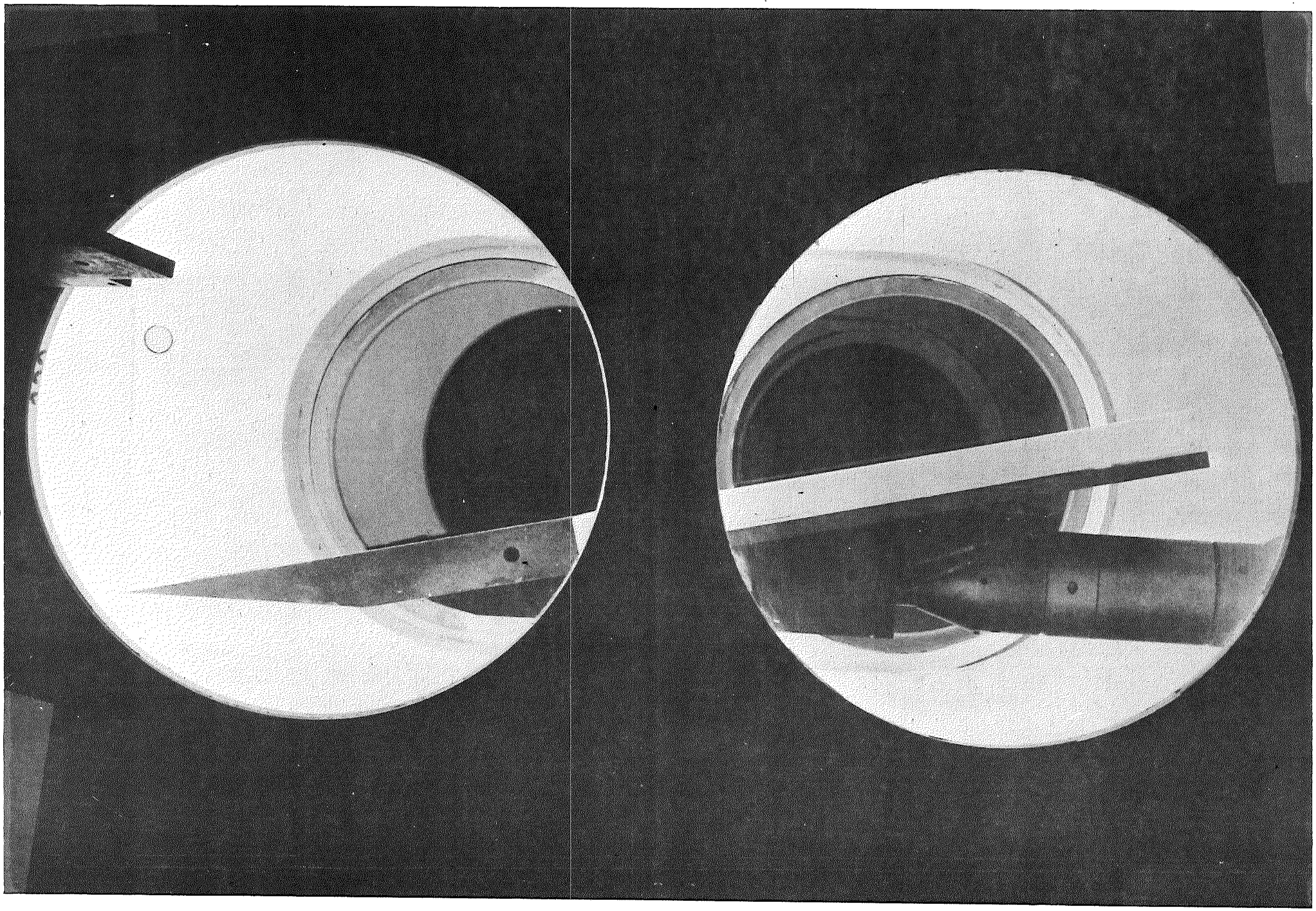
a. Installation Photograph

Figure 5. Installation of Test Specimen on Wedge



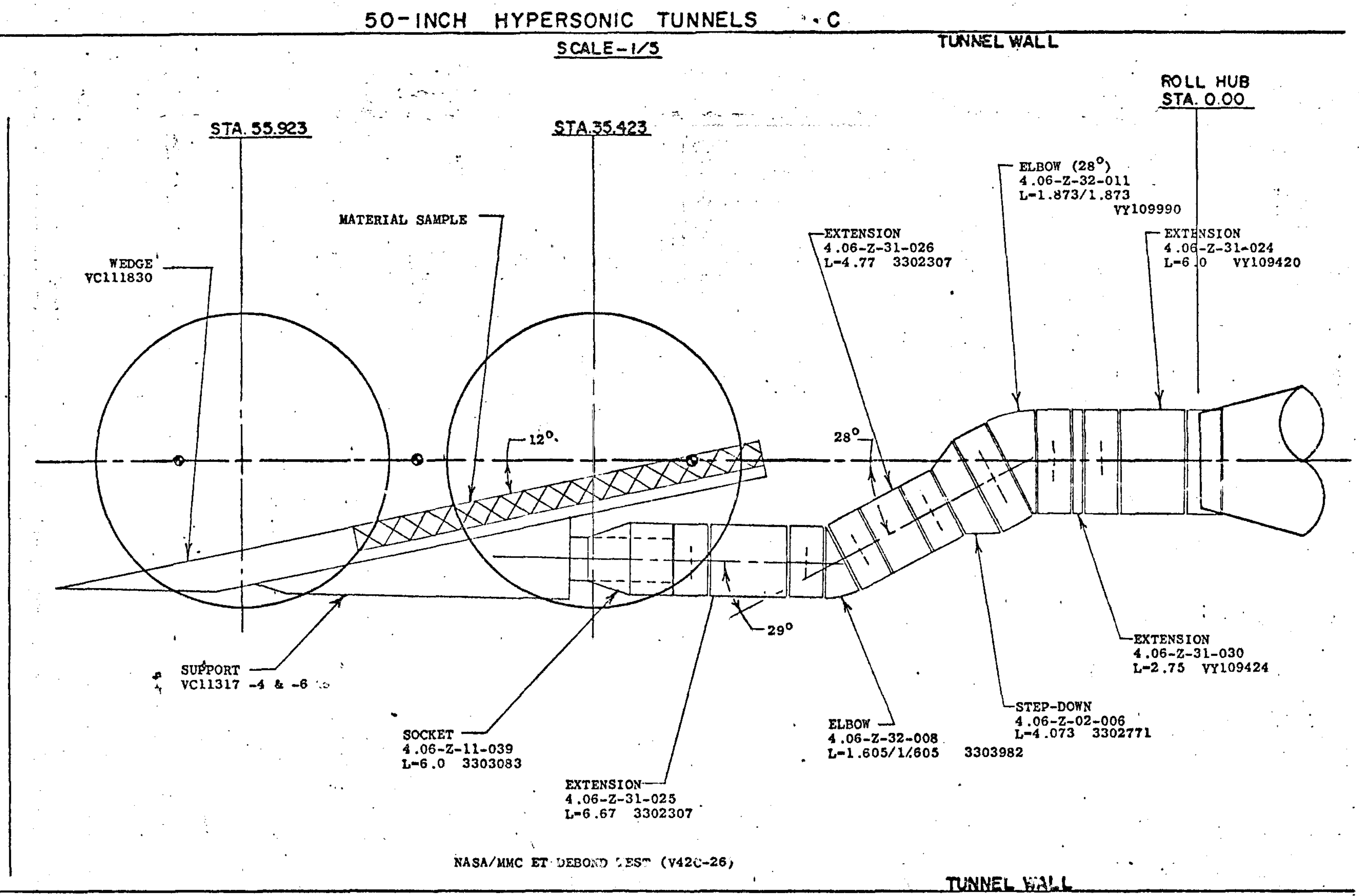

b. Sketch of Materials Testing Wedge

Figure 5. Concluded



a. Installation Photograph

Figure 6. Installation in Tunnel C




b. Installation Sketch

Figure 6. Concluded

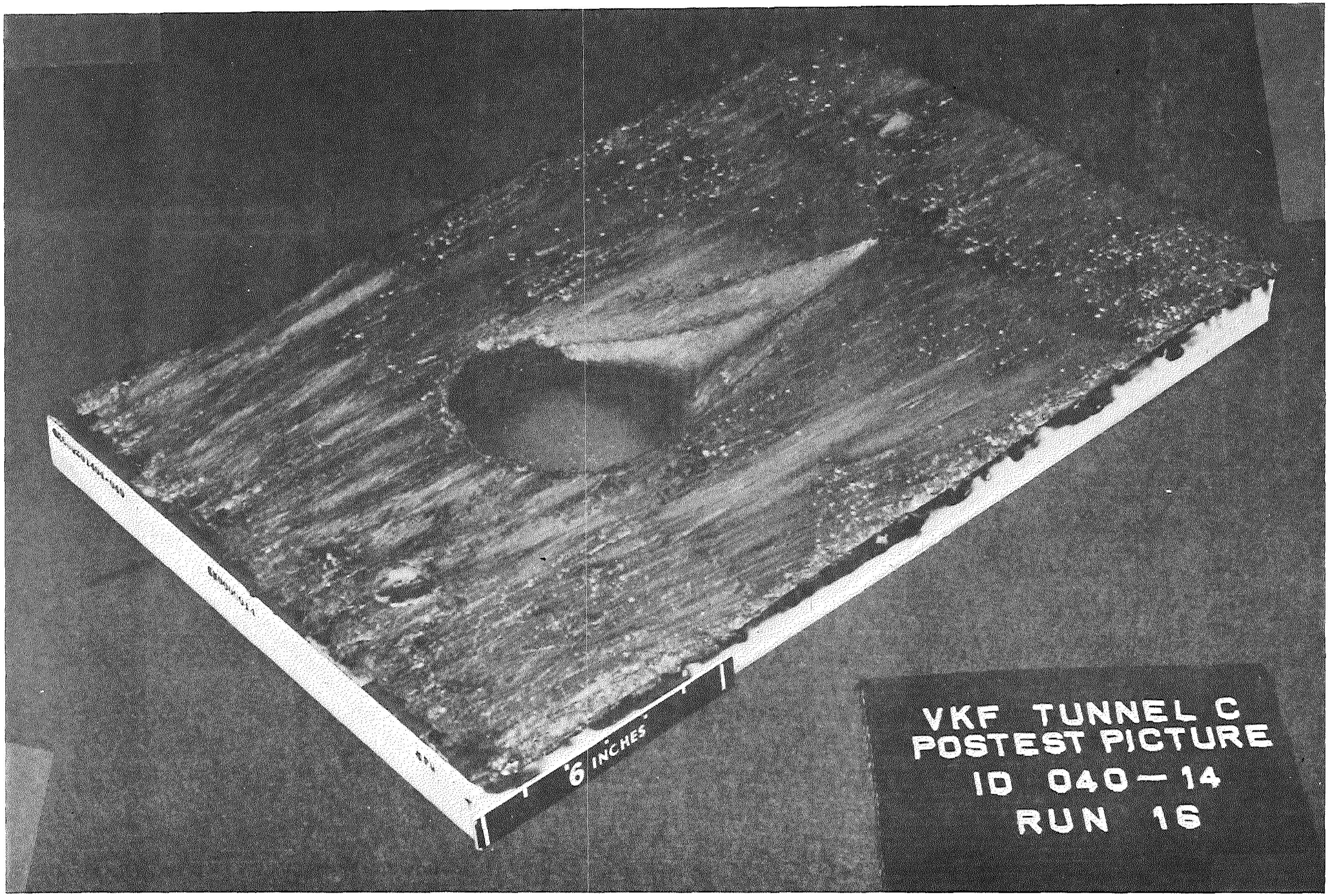



Figure 7. Posttest Photograph

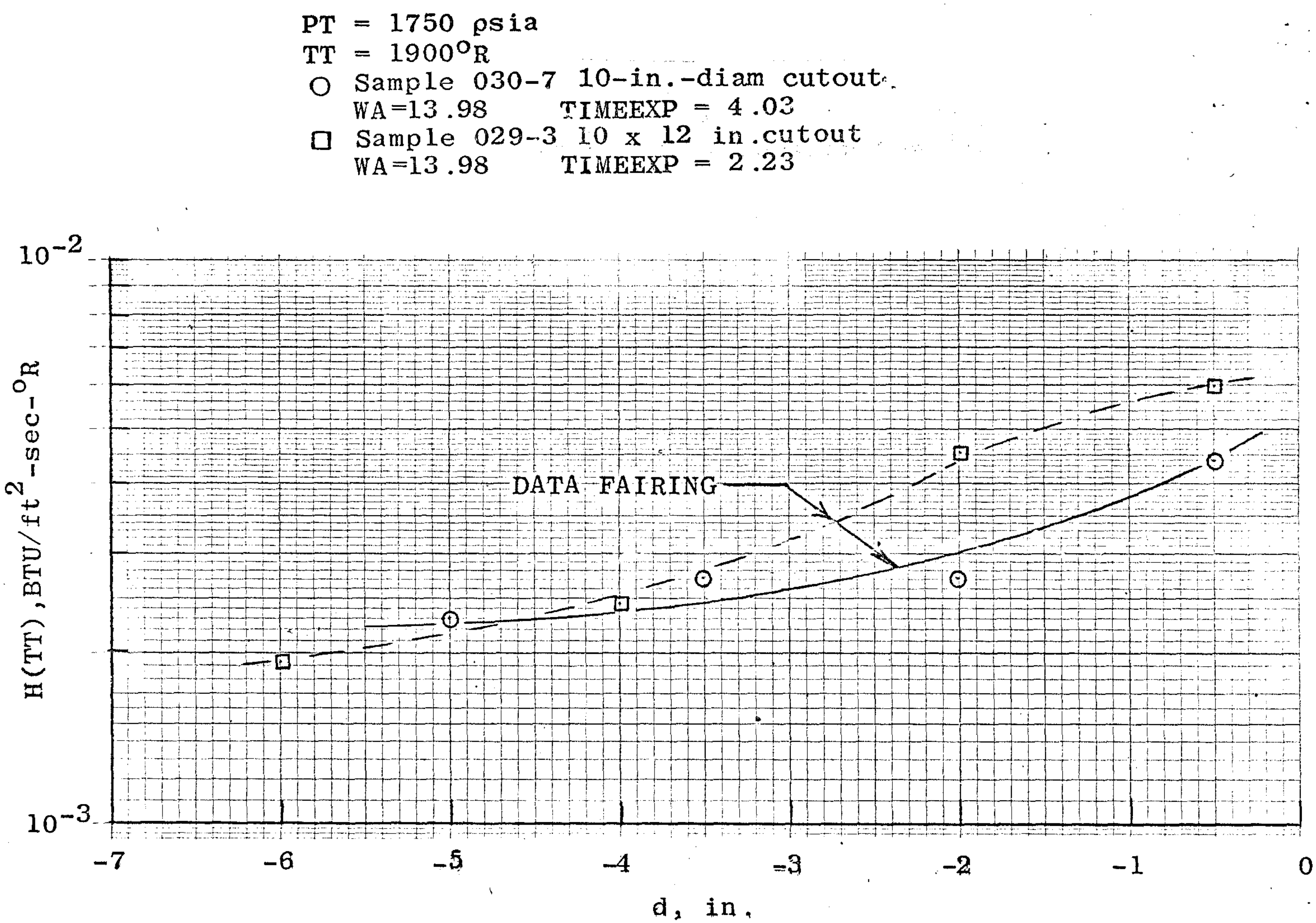



Figure 8. Representative Heat-Transfer Coefficient Data

APPENDIX II

TABLES

TABLE 1

## Model Identification and Configuration Codes

### Martin Marietta Identification Code

xxx - xx

SERIAL NUMBER

| | |
|---|---|
| 029 | 10"x12" cutout |
| 030 | 10"-diam cutout |
| 039 | 8"-diam cutout |
| 040 | 5"-diam cutout |
| 000 | No Cutout |

EXAMPLE

029-03 = 10" x 12" cutout Serial No. 3

### VKF Configuration Code

xxxx

SERIAL NUMBER

| | |
|---|---|
| 04 | 10" x 12" cutout (029) |
| 03 | 10"-diam cutout (030) |
| 02 | 8"-diam cutout (039) |
| 01 | 5"-diam cutout (040) |
| 00 | No Cutout (000) |

EXAMPLE

0403 = 10" x 12" cutout Serial No. 3 (029-03)

TABLE 2. ESTIMATED UNCERTAINTIES

a. Basic Measurements

| Parameter Designation | STEADY-STATE ESTIMATED MEASUREMENT* Precision Index (S) Percent of Reading | Unit of Measurement | Degree of Freedom | Bias (B) Percent of Reading | Unit of Measurement | Uncertainty $\pm(B + t_{95}S)$ Percent of Reading | Unit of Measurement | Range | Type of Measuring Device | Type of Recording Device | Method of System Calibration |
|---|---|---|---|---|---|---|---|---|---|---|---|
| STILLING CHAMBER, PRESSURE, PT, psia | | 0.002<br>0.002<br>0.007 | >30<br>>30<br>>30 | | 0.011 | 0.015<br>(0.2% + 0.004)<br>(0 2% + 0.014) | | <5.5<br><15<br><60 | Bell & Howell force balance pressure transducer | Digital data acquisition system analog-to-digital converter | In-place application of multiple pressure levels measured with a pressure measuring device calibrated in the standards laboratory |
| | | 0.62<br>0.62 | >30<br>>30 | 0.16 | 0.8 | (0.8psi + 1.24psi) 2.04<br>(0.15% + 1.24psi) | | >156.25<500<br>>500<2500 | Wiancko variable reluctance pressure transducer | | |
| TOTAL TEMPERATURE, TT, °F | | 1<br>1 | >30<br>>30 | 0.375 | 2 | | 4<br>±(.375% +2°F) | 32 to 530 | Chromel[R]-Alumel[R] thermocouple | Doric temperature instrument digital multiplexer | Thermocouple verification of NBS conformity/voltage substitution calibration |
| PITCH ANGLE, ALPHI | | 0.025 | >30 | | | | 0.05 | 15 | Potentiometer | | Heidenhain rotary encoder ROD700 Resolution: 0.0006° Overall accuracy. 0.001° |
| TIME | | $5x10^{-4}$ | >30 | Runtime(sec)x5x $10^{-6}$ | | +Runtime(sec)x5x $10^{-6}$)+$10^{-3}$ | | ms to 365 days | Systron Donner time code generator | Digital data acquisition system | Instrument lab calibration against Bureau of Standards |
| HEAT TRANSFER, QDOT, BTU/$ft^2$-sec | 1.5 | 0.015 | >30<br>>30 | 2<br>2 | | (0.03 + 2%)<br>5% | | <1<br>1 to 10 | Gardon gage | Digital data acquisition system analog-to-digital converter | Radiant heat source and secondary standard |
| $E_{mv}$ | 0.1 | | >30 | 0.01 | | (0.2% + 0.01) | | | DEC-10/Multiverter Preston amplifier | | Millivolt standard, referenced to lab standard |
| TEMPERATURE, TGE, °F | | 1<br>1 | >30<br>>30 | 3/8% | 2 | (3/8% + 2°F) | 4 | 32 to 530<br>530 to 2300 | CrAl thermocouple | | |

*Thompson, J. W. and Abernethy, R. B. et al. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.

TABLE 2. Concluded

b. Calculated Parameters

| Parameter Designation | STEADY-STATE ESTIMATED MEASUREMENT* | | | | | | | Range |
|---|---|---|---|---|---|---|---|---|
| | Precision Index (S) | | | Bias (B) | | Uncertainty $\pm(B + t_{95}S)$ | | |
| | Percent of Reading | Unit of Measurement | Degree of Freedom | Percent of Reading | Unit of Measurement | Percent of Reading | Unit of Measurement | |
| H(TT),BTU/ft$^2$-sec-$^o$R | 2.0 | | 30 | 2.0 | | 6.0 | | |
| M | | 0.008<br>0.007<br>0.006<br>0.004 | 30<br>30<br>30<br>30 | | 0+<br>0+<br>0+<br>0+ | | 0.016<br>0.014<br>0.012<br>0.008 | 2.0<br>10.02<br>10.05<br>10.11 |
| QDOT-O,BTU/ft$^2$-sec | 2.0 | | 30 | 2.0 | | 6.0 | | |
| TW,$^o$R | 0.2 | | 30 | 0.4 | | 0.8 | | All |
| WA,deg | | 0.05 | 30 | | 0+ | | 0.10 | All |

*Abernethy, R. B. et al. and Thompson, J. W. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.

+Assumed to be zero

TABLE 3. Camera Summary

| | Camera Type | Frame Rate | Camera Location | Sample View | Film Roll No. |
|---|---|---|---|---|---|
| Camera 1 | Varitron 70mm color still | 1 per 2 sec | Top upstream window of 2-port window | Top view of sample on centerline with projected grid lines | 0819 |
| Camera 2 | Milliken 16mm color movie | 24 | Top upstream window of 2-port window | Top view of sample on centerline with projected grid lines | 4372<br>4373 |
| Camera 3 | Milliken 16mm color movie | 24 | Operating side upstream window | Left side view of forward portion of sample on center-line | 4374<br>4375 |
| Camera 4 | Varitron shadow-graph still | 1 per 25 sec | Operating side downstream window | Left side view of sample and wedge on centerline | 0795 |
| Camera 5 | Sony black/white videocamera | N/A | Top forward window of 2-port window | Top view of sample | |

TABLE 4. Test Summary

PT = 1750 PSIA TT = 1900$^{o}$R

| RUN | MODEL I.D. | CONFIGURATION CODE | WEDGE ANGLE | TIME EXPT | APPROX Q-DOT-0 |
|---|---|---|---|---|---|
| 1 | 029-03 | 0403 | 3 | 37.03 | - |
| 2 | 030-07 | 0307 | 14 | 2.74 | 6 |
| 3 | ↓ | ↓ | 19 | 2.78 | 8 |
| 4 | | | 23.4 | 14.22 | 10 |
| 5 | 029-04 | 0404 | 14 | 24.19 | 6 |
| 6 | 029-02 | 0402 | 19 | 19.93 | 8 |
| 7 | 029-01 | 0401 | 23.4 | 15.33 | 10 |
| 8 | 030-05 | 0305 | 14 | 32.25 | 6 |
| 9 | 030-06 | 0306 | 19 | 21.31 | 8 |
| 10 | 030-08 | 0308 | 23.4 | 16.59 | 10 |
| 11 | 039-09 | 0209 | 14 | 31.98 | 6 |
| 12 | 039-10 | 0210 | 19 | 22.62 | 8 |
| 13 | 039-11 | 0211 | 23.4 | 16.55 | 12 |
| 14 | 039-12 | 0212 | 5 | 30.84 | ~2 |
| 15 | 040-13 | 0113 | 14 | 30.84 | 6 |
| 16 | 040-14 | 0114 | 19 | 21.25 | 8 |
| 17 | 040-15 | 0115 | 23.4 | 17.13 | 10 |
| 18 | 040-16 | 0116 | 5 | 32.34 | 2 |
| 19 | 000-17 | 0017 | 19 | 33.47 | 8 |
| 20 | 000-18 | 0018 | 19 | 33.31 | 8 |
| 21 | 000-19 | 0019 | 19 | 22.48 | 8 |

NOTES:
1. See Table 1 for model identification and configuration code summary.
2. The approximate QDOT level is based on previous calibration data.
3. Wedge angle was varied on Run 1. See text (Section 3.2) for explanation.

467

APPENDIX III

REFERENCE HEAT-TRANSFER COEFFICIENT

In presenting heat-transfer coefficient results it is convenient to use reference coefficients to normalize the data. For this test the heat-transfer measurements obtained at the bottom of the cavities were normalized using the heat-transfer coefficient which would have been expected on a flat panel in the absence of the cavity. The value of the reference heat-transfer coefficient was obtained from flat-plate calibration data obtained with the same wedge during previous tests at the same conditions in Tunnel C.* Since the tunnel conditions are the same the heat-transfer coefficient at a given location on the panel is a function only of the wedge angle. A location of X = 29.5 was chosen as being representative of the region where the cavities were cut in the panels for this test. Then, from the calibration data, the flat-plate reference heat-transfer coefficient was determined to be

$$H(FP) = (2.198 \times 10^{-4})(WA) + 3.67 \times 10^{-4} \text{ Btu/ft}^2\text{sec-°R}$$

*Stallings, D. W. "Space Shuttle External Tank Instrumentation Evaluation." AEDC-TSR-79-V11, February 1979.

# APPENDIX IV

## SAMPLE TABULATED DATA

ARVIN/CALSPAN FIELD SERVICES, INC.
AEDC DIVISION
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE
NASA/MMC ET TPS DEBOND TEST
PAGE 2

DATE COMPUTED 6-MAR-81
TIME COMPUTED 14:11:12
DATE RECORDED 5-MAR-81
TIME RECORDED 1:20:35
PROJECT NUMBER V41C-26

| RUN | SAMPLE | ALPHI DEG | WA DEG | CR IN | TIMEINJ SEC | TIMECL HOUR | MIN | SEC | MSEC | TIMEEXPT SEC |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 029- 3 | -2.06 | 14.06 | 25.00 | 2.806 | 1 | 20 | 58 | 143 | 37.03 |

| M | PT PSIA | TT DEG R | T DEG R | P PSIA | Q PSIA | V FT/SEC | RHO LBM/FT3 | MU LBF-SEC/FT2 | RE FT-1 | ITT BTU/LBM |
|---|---|---|---|---|---|---|---|---|---|---|
| 10.10 | 1749.99 | 1898.7 | 93.5 | 3.786E-02 | 2.70 | 4786.1 | 1.093E-03 | 7.524E-08 | 2.161E+06 | 4.779E+02 |

GARDON GAGE DATA AT TIMEEXP 4.03 SEC WA 13.98 DEG

| GAGE | X/L | Y/B | TGE (DEG R) | TW (DEG R) | QDOT (BTU/FT2-SEC) | H(TT) (BTU/FT2-SEC-R) | H(TT)/H(FP) | QDOT-O (BTU/FT2-SEC) | H(FP) (BTU/FT2-SEC-R) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.64 | 0.00 | 544.2 | 552.5 | 2.40 | 1.780E-03 | 5.173E-01 | 2.561E+00 | 3.441E-03 |
| 2 | 0.71 | 0.00 | 544.2 | 553.3 | 2.54 | 1.890E-03 | 5.492E-01 | 2.720E+00 | 3.441E-03 |
| 3 | 0.76 | 0.00 | 554.8 | 569.5 | 3.26 | 2.456E-03 | 7.138E-01 | 3.535E+00 | 3.441E-03 |
| 4 | 0.81 | 0.17 | 550.9 | 581.0 | 6.97 | 5.290E-03 | 1.537E+00 | 7.612E+00 | 3.441E-03 |
| 5 | 0.81 | 0.00 | 550.7 | 575.3 | 5.92 | 4.472E-03 | 1.300E+00 | 6.436E+00 | 3.441E-03 |
| 6 | 0.81 | -0.17 | 550.9 | 584.4 | 8.19 | 6.230E-03 | 1.811E+00 | 8.965E+00 | 3.441E-03 |
| 7 | 0.84 | 0.00 | 572.1 | 600.1 | 7.90 | 6.082E-03 | 1.768E+00 | 8.753E+00 | 3.441E-03 |

GARDON GAGE DATA AT TIMEEXP 7.43 SEC WA 13.97 DEG

| GAGE | X/L | Y/B | TGE (DEG R) | TW (DEG R) | QDOT (BTU/FT2-SEC) | H(TT) (BTU/FT2-SEC-R) | H(TT)/H(FP) | QDOT-O (BTU/FT2-SEC) | H(FP) (BTU/FT2-SEC-R) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.64 | 0.00 | 567.1 | 580.2 | 3.77 | 2.862E-03 | 8.327E-01 | 4.118E+00 | 3.437E-03 |
| 2 | 0.71 | 0.00 | 567.1 | 576.8 | 2.71 | 2.048E-03 | 5.957E-01 | 2.946E+00 | 3.437E-03 |
| 3 | 0.76 | 0.00 | 582.4 | 597.2 | 3.27 | 2.512E-03 | 7.308E-01 | 3.614E+00 | 3.437E-03 |
| 4 | 0.81 | 0.17 | 583.2 | 598.4 | 3.52 | 2.706E-03 | 7.873E-01 | 3.894E+00 | 3.437E-03 |
| 5 | 0.81 | 0.00 | 583.1 | 595.8 | 3.06 | 2.349E-03 | 6.835E-01 | 3.381E+00 | 3.437E-03 |
| 6 | 0.81 | -0.17 | 583.2 | 596.6 | 3.28 | 2.522E-03 | 7.337E-01 | 3.629E+00 | 3.437E-03 |
| 7 | 0.84 | 0.00 | 618.4 | 628.9 | 2.95 | 2.321E-03 | 6.752E-01 | 3.340E+00 | 3.437E-03 |

GARDON GAGE DATA AT TIMEEXP 10.93 SEC WA 14.57 DEG

| GAGE | X/L | Y/B | TGE (DEG R) | TW (DEG R) | QDOT (BTU/FT2-SEC) | H(TT) (BTU/FT2-SEC-R) | H(TT)/H(FP) | QDOT-O (BTU/FT2-SEC) | H(FP) (BTU/FT2-SEC-R) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.64 | 0.00 | 592.9 | 608.2 | 4.43 | 3.436E-03 | 9.532E-01 | 4.945E+00 | 3.605E-03 |
| 2 | 0.71 | 0.00 | 592.9 | 604.4 | 3.21 | 2.483E-03 | 6.888E-01 | 3.573E+00 | 3.605E-03 |
| 3 | 0.76 | 0.00 | 611.4 | 629.3 | 3.96 | 3.119E-03 | 8.651E-01 | 4.488E+00 | 3.605E-03 |
| 4 | 0.81 | 0.17 | 608.7 | 622.0 | 3.06 | 2.396E-03 | 6.646E-01 | 3.448E+00 | 3.605E-03 |
| 5 | 0.81 | 0.00 | 611.4 | 626.5 | 3.64 | 2.858E-03 | 7.929E-01 | 4.113E+00 | 3.605E-03 |
| 6 | 0.81 | -0.17 | 608.7 | 625.1 | 3.99 | 3.135E-03 | 8.697E-01 | 4.512E+00 | 3.605E-03 |
| 7 | 0.84 | 0.00 | 641.4 | 649.5 | 2.28 | 1.828E-03 | 5.069E-01 | 2.630E+00 | 3.605E-03 |

a. Gardon Gage Data

Sample 1. Sample Data

ARVIN/CALSPAN FIELD SERVICES, INC.
AEDC DIVISION
VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENNESSEE
NASA/MMC ET TPS DEBOND TEST
PAGE 1

DATE COMPUTED 5-MAR-81
TIME COMPUTED 02:18:52
DATE RECORDED 5-MAR-81
TIME RECORDED 2:18: 1
PROJECT NUMBER V41C-26

| RUN | SAMPLE | ALPHI DEG | WA DEG | CR IN | TIMEINJ SEC | TIMECL HOUR | TIMECL MIN | TIMECL SEC | TIMECL MSEC | TIMEEXPT SEC |
|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 030- 5 | -2.05 | 14.05 | 25.00 | 2.932 | 2 | 18 | 20 | 483 | 32.25 |

| M | PT PSIA | TT DEG R | T DEG R | P PSIA | Q PSIA | V FT/SEC | RHO LBM/FT3 | MU LBF-SEC/FT2 | RE FT-1 | ITT BTU/LBM |
|---|---|---|---|---|---|---|---|---|---|---|
| 10.10 | 1747.73 | 1902.7 | 93.7 | 3.780E-02 | 2.70 | 4791.6 | 1.089E-03 | 7.541E-08 | 2.150E+06 | 4.790E+02 |

| PIC NO. | TIME SEC | TIMEEXP SEC |
|---|---|---|
| | SHADOWGRAPH TAKEN AT 2.5 SECONDS. | |
| 1 | 4.16 | 2.52 |
| 2 | 6.20 | 4.56 |
| 3 | 8.25 | 6.61 |
| 4 | 10.30 | 8.66 |
| 5 | 12.36 | 10.71 |
| 6 | 14.38 | 12.73 |
| | SHADOWGRAPH TAKEN AT 12.8 SECONDS. | |
| 7 | 16.44 | 14.79 |
| 8 | 18.47 | 16.83 |
| 9 | 20.53 | 18.88 |
| 10 | 22.59 | 20.94 |
| 11 | 24.64 | 23.00 |
| | SHADOWGRAPH TAKEN AT 23.1 SECONDS. | |
| 12 | 26.69 | 25.04 |
| 13 | 28.73 | 27.08 |
| 14 | 30.78 | 29.13 |
| 15 | 32.84 | 31.19 |
| | 32.25 | MODEL HAS LEFT CENTERLINE |

b. Photograph Data

Sample 1. Concluded